EXHAUST DISPERSION ANALYSIS FROM LARGE SOLID PROPELLANT ROCKET MOTOR FIRING USING HYSPLIT MODEL OVER SATISH DHAWAN SPACE CENTRE (SDSC SHAR)

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ABSTRACT

Large solid propellant rocket motor, meant for next generation launch vehicle was static tested at SDSC SHAR. During burning of 103 sec, 207 tonnes of HTBP based solid propellant motor was burnt and major exhaust pollutants are Aluminum Oxide (Al_2O_3), Hydrogen Chloride (HCl) and Carbon Monoxide (CO). Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model is used to predict the dispersion of exhaust pollutant in the form of vapour and ground level concentrations. HYSPLIT model is run through a Graphical User Interface (GUI) for ease in setting up trajectory, concentration or deposition guidance. HYSPLIT was configured to simulate the pollutant dispersion from Rocket static test bed source location using meteorological input from the Meso-scale Model version 5 (MM5). HYSPLIT simulated from 08:00 IST to 10:00 IST on the day of test at ground level, 10m, 100m, 300m and 500m altitudes. GUI converted the MM5 meteorological grids into HYSPLIT binary format, model was run and post-processed the data to create output graphics and displayed in KMZ Goggle Earth. MM5 model initialized with local observations like GPS RS, AWS and MET tower observations and are run at 3 km spatial resolution and with thirty-one vertical levels. MM5 provided input into HYSPLIT that may better predict the unique meso-scale environment. Rocket motor emission rate, composition and duration inputs are configured in HYSPLIT. Attempts were made to simulate HCl, CO concentrations at elevations of 10m, 100m, 300m and 500m altitudes and Al_2O_3 particle deposition at ground. In future work, HYSPLIT dispersion simulations will be validated with the observations.

1.0 Introduction

Air quality monitoring is a paramount requirement of safety, health and environment divisions of SDSC SHAR, Andhra Pradesh, India. Since 2000, SDSC SHAR has constantly analyzing the atmospheric dispersion models for predicting the behavior of rocket exhausts in the atmosphere and propellant vapor dispersion from storages and as well as launch vehicles. The pollutant dispersion analysis are routinely used to assess the environmental impact of exhaust pollutants from rockets with respect to permissible toxicity thresholds and air quality standards. Beyond analyzing the environmental impact, the dispersion data is used to map the safe corridor for human life and work facilities. This paper deals with the exhaust dispersion analysis from large solid propellant rocket motor static test firing on 24th January 2010 02:30 UTC or 08:00 IST (Fig.1) using HYSPLIT model over SDSC SHAR.

2.0 Large Solid Propellant Rocket Motor (S200)

The large solid propellant rocket motor, S200 consists of HTPB based composite propellant with 86% solid ingredient loading. There are three segments in the motor. The overall length is 21.9m. Diameter and propellant mass is 3200 mm and 207 tones respectively. When this solid motor of S200 rocket is static test fired, the major exhaust pollutants are Aluminium Oxide (Al_2O_3) – 34%, Carbon Monoxide (CO) – 26.6% and Hydrogen Chloride (HCl) – 20.7%. The emission rate of the exhaust pollutant is considered as 2009 kg/s. Based on the above data the vapour dispersion of HCl, CO and particle deposition of Al_2O_3 was analysed using HYSPLIT model at different altitudes.

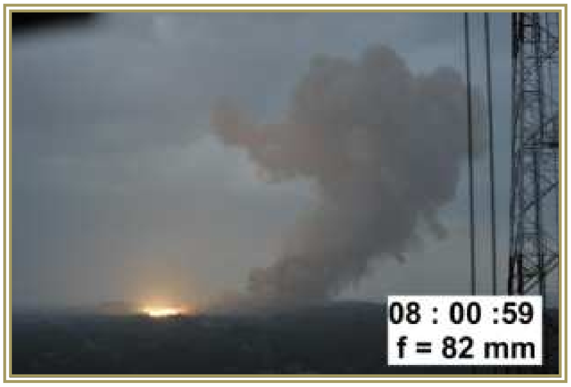


Fig.1 View of S200 static test and plume rising

3.0 HYSPLIT Model Description

The HYSPLIT model has been developed at the NOAA Air Resources Laboratory (ARL). The model is a complete system for computing atmospheric trajectories, complex dispersion and simulations using either puff or Lagrangian particles (Draxler 2011). HYSPLIT applications include tracking and forecasting the release of pollutant material, air-parcel trajectories, volcanic ash, and smoke from wildfires. HYSPLIT uses gridded meteorological data to drive the trajectories and concentrations either forwards or backwards in time at regular time intervals. The HYSPLIT model uses grid meteorological data and dispersion rate is calculated from the vertical diffusivity profile, wind shear and horizontal deformation of the wind field. Air concentrations are calculated at the specific grid points for puffs and cell average concentrations for particles. The software is written mainly in Fortran with several modules in C code.

4.0 Meteorological Model (MM5) data for Hysplit

The meteorological modelling system is based on the PSU/NCAR Mesoscale Model (MM5). The well known MM5 system is a parallelized, limited area, non-hydrostatic, terrain following and sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation (Dudhia, J. et al., 2005). Pre-processors are used to define computing grids, to assimilate global scale hydrostatic models outputs (global analysis and forecasts), topography, land use data and thus prepare initialization and boundary conditions input files for MM5. For Hysplit, NCEP/GFS global data with 3 hours and 0.5° X 0.5° resolutions are used.

The simulations are performed in a nested domains mode, which allows to consider in a single run both large calculation domains and high resolutions. The inner domains at high resolution are defined into a larger domain at lower resolution (coarse domain). Simulations are also performed in a two-way mode: calculations for all domains are carried out simultaneously, so that boundary conditions are provided at each time step to inner domains at high resolution. This method also allows feedback on the coarse domain. The horizontal resolution for the outer domain is 9 km and Inner domain is over Southern Peninsular India covering SDSC SHAR region with 3 km resolution. Both domains have 31 vertical levels defined from soil to 10000Pa (approximately 15000m).

The MM5 parameterization used is as follows: Reisner Graupel (Reisner2) explicit moisture scheme, Kain-Fritsch-2 cumulus parameterization, MRF planetary boundary layer scheme, RRTM radiation scheme, and five-layer soil model. MM5 model integrated on 24th Jan 2010 with 00UTC initial conditions, assimilation with GPS RS, meso- network AWS and other available observations. Model output hourly dumping made available to HYSPLIT runs for Static Test time at 02:30 UTC. Continues Meteorological Surface and soundings are measured from 00UTC on the test day. MM5 model derived Temperature, Relative humidity and wind profiles are validated with GPS-Radiosonde profiles shown in Fig.2 & 3. Validation results are confirming that MM5 model able to predict the lower tropospheric moisture intrusion and lower level strong easterlies due to Easterly wave activity over SHAR region.

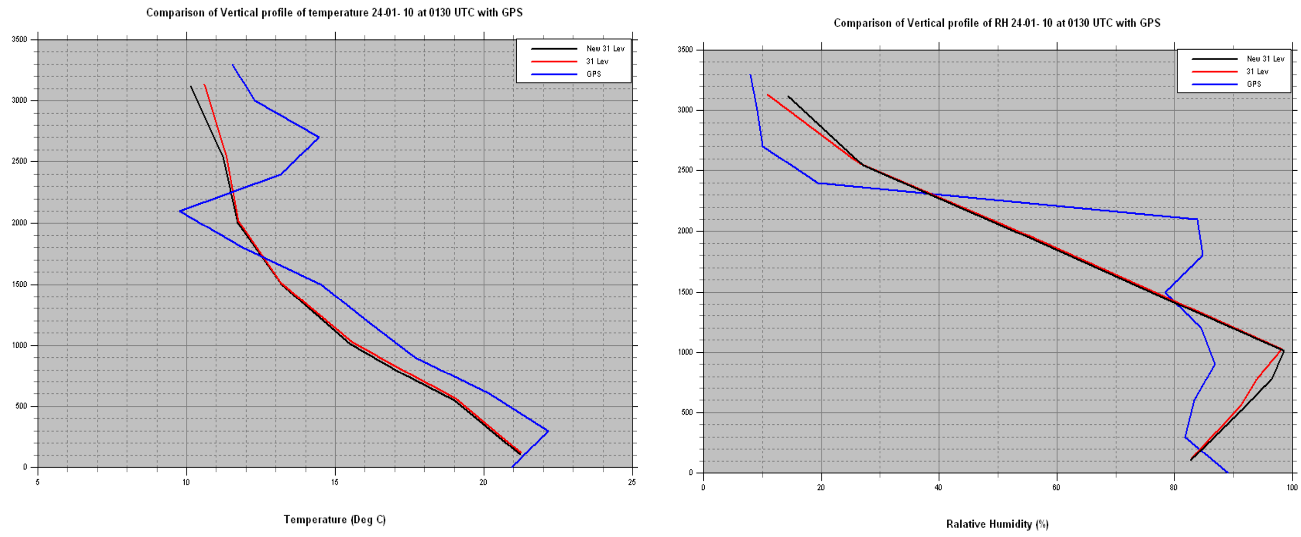


Fig.2 Comparison of MM5 model derived & GPS-Radiosonde Temperature and RH profiles over SDSC SHAR region at 01:30 UTC

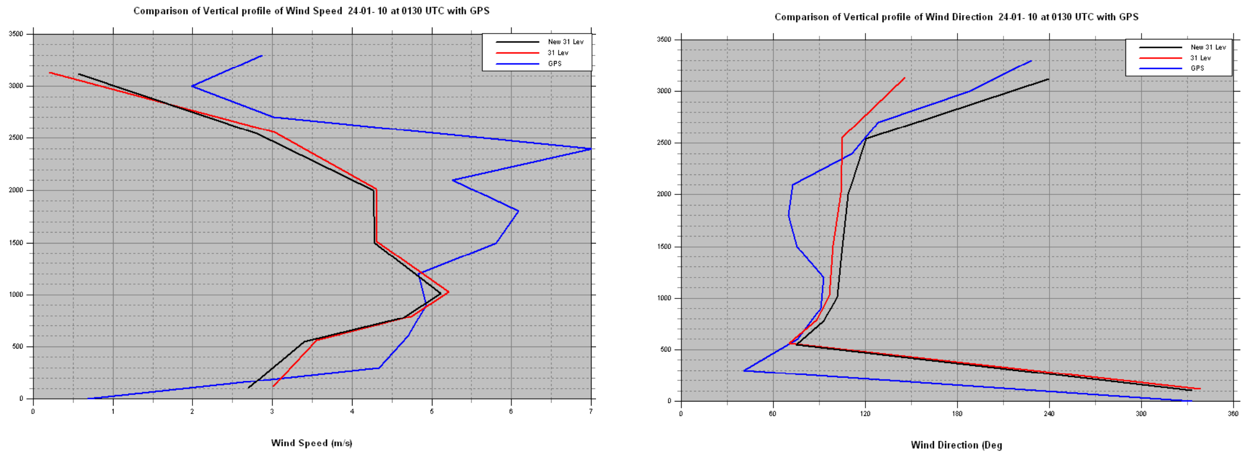


Fig.3 GPS RS Wind speed and direction profiles comparison with MM5 *derived wind profiles for SDSC SHAR region at 01:30 UTC*

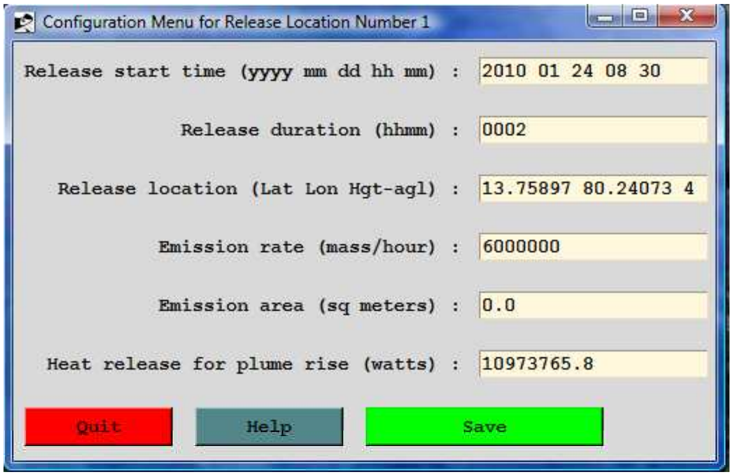
5.0 HYSPLIT Configuration

Around 207 tones of solid propellant S200 rocket motor is statically test fired at ground level in 103 seconds. MM5 model meteorological gridded data to HYSPLIT, ARL conversion program used to convert model required horizontal grid format. Configuration of HYSPLIT model is based on actual data and shown given below, the corresponding configuration of source emission rate, location, duration, setup and turbulence in HYSPLIT software is shown in Fig 4 and Fig 5. .

Total Emission Rate	: 60,00,000 kg/hr
Total Heat Release	: 10973765.8 W
Release Duration	: ~2 Min

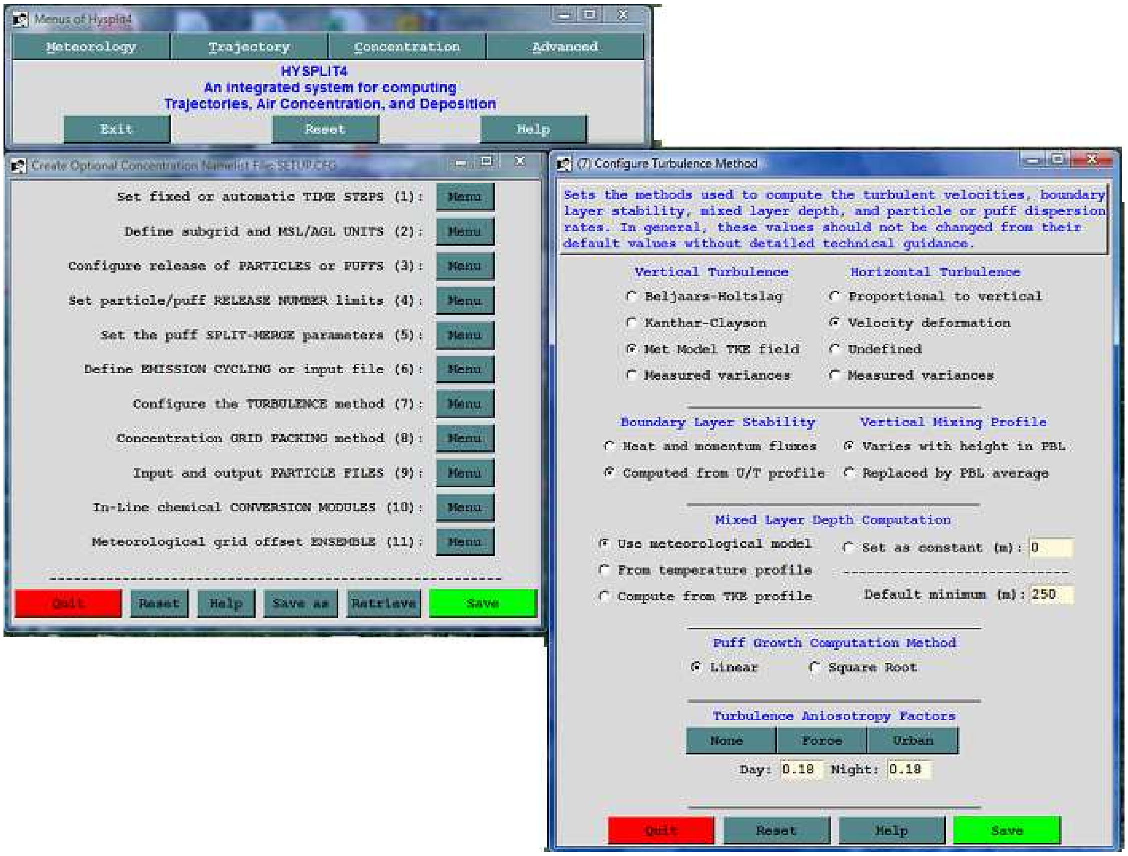
Pollutants: *Rocket exhaust propellants are configured based on lab results, shown below*

Particles	Al_2O_3 (34%)	Emission rate	: 20,40000 kg/hr
		Diameter	: 100 µm
		Density	: 4 g/cc
		Molecular weight	: 101.9 g/mole
Gases	HCl (20.7%)	Emission rate	: 12,42000 kg/hr
		Density	: 1.27 g/cc
		Molecular weight	: 36.46 g/mole
	CO (26.64%)	Emission rate	: 15,98400 kg/hr
		Density	: 1.84 g/cc
		Molecular weight	: 28.01 g/mole



Release start time (yyyy mm dd hh mm) : 2010 01 24 08 30
Release duration (hhmm) : 0002
Release location (Lat Lon Hgt-agl) : 13.75897 80.24073 4
Emission rate (mass/hour) : 6000000
Emission area (sq meters) : 0.0
Heat release for plume rise (watts) : 10973765.8

Fig.4 HYSPLIT Configuration - source emission rate, location and duration



HYSPLIT4
An integrated system for computing
Trajectories, Air Concentration, and Deposition

Set fixed or automatic TIME STEPS (1): Menu
Define subgrid and MSL/AGL UNITS (2): Menu
Configure release of PARTICLES or PUFFS (3): Menu
Set particle/puff RELEASE NUMBER limits (4): Menu
Set the puff SPLIT-MERGE parameters (5): Menu
Define EMISSION CYCLING or input file (6): Menu
Configure the TURBULENCE method (7): Menu
Concentration GRID PACKING method (8): Menu
Input and output PARTICLE FILES (9): Menu
In-Line chemical CONVERSION MODULES (10): Menu
Meteorological grid offset ENSEMBLE (11): Menu

Sets the methods used to compute the turbulent velocities, boundary layer stability, mixed layer depth, and particle or puff dispersion rates. In general, these values should not be changed from their default values without detailed technical guidance.

Vertical Turbulence
○ Beljaars-Holtslag
○ Kanthar-Clayson
● Met Model TKE field
○ Measured variances

Horizontal Turbulence
○ Proportional to vertical
● Velocity deformation
○ Undefined
○ Measured variances

Boundary Layer Stability
○ Heat and momentum fluxes
● Computed from U/T profile

Vertical Mixing Profile
● Varies with height in PBL
○ Replaced by PBL average

Mixed Layer Depth Computation
● Use meteorological model
○ From temperature profile
○ Compute from TKE profile
○ Set as constant (m): 0
Default minimum (m): 250

Puff Growth Computation Method
● Linear
○ Square Root

Turbulence Aniosotropy Factors
Day: 0.18 Night: 0.18

Fig.5 Setup & Turbulence - HYSPLIT Configurations

6.0 Synoptic Weather on the day of static test

On S200 rocket motor static test day, Easterly wave active over Southern peninsular India and effecting Coastal Tamilnadu and extreme South Coastal Andhra. In Fig.6, Kalpana-1 EIR image shows low clouds and 500m level Easterly wave flow over SDSC SHAR region. Static test time around 2:30 UTC, cloudy sky and isolated drizzles experienced over the region.

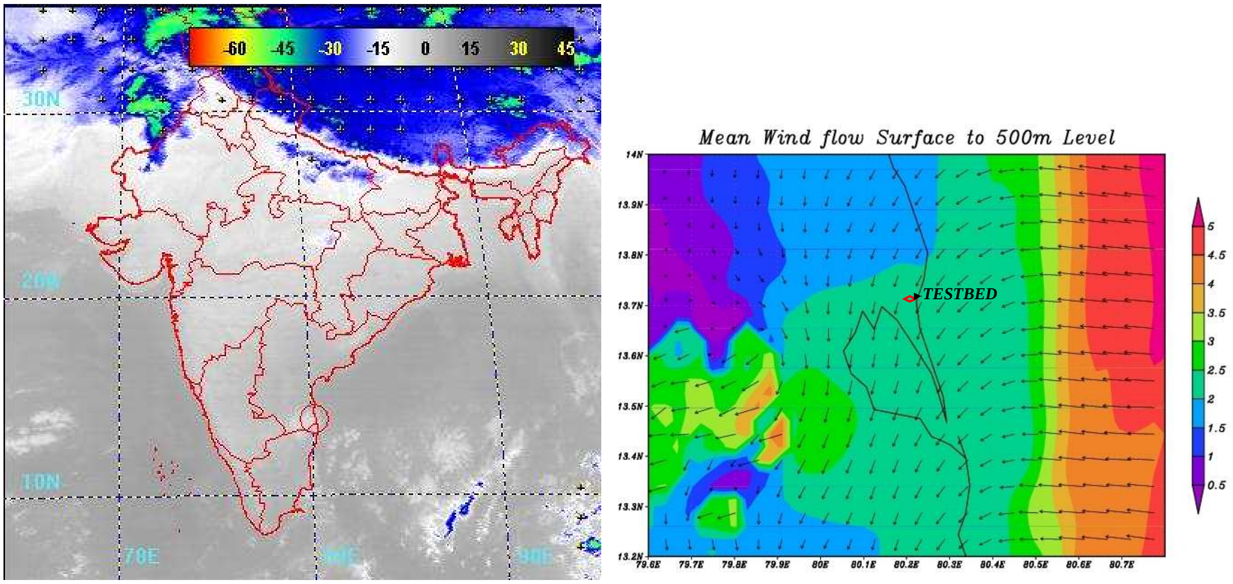


Fig.6 Kalpana-1 EIR Brightness Temperature at 02:30 UTC and 24th Jan 2010 and MM5 Model analysis - 500m altitude mean wind flow

7.0 Results and Discussion

The firing of the solid rocket motor during the static test gives a large cloud of hot and buoyant exhaust products near ground level initially (Marco Cencetti, et al., 2007). The cloud rises and entrains ambient air until the cloud reaches an approximate equilibrium with ambient conditions like temperature, density, speed and turbulence. The cloud is then called the stabilized cloud. Based on Morten, Taylor and Turner model, stabilized cloud base altitude or the plume rise is calculated as given below:

$$\text{Plume Rise } H = 2.675\, Q^{1/4}$$

$$Q = m\, C_p\, (T_e - T_a)$$

Where

H = Final height in metre
Q = Rate of release of heat in joules
m = Emission rate of exhaust gas in kg/s
C_p = Specific heat of exhaust gas in J/kgK
T_e = Exhaust gas temperature in K
T_a = Ambient temperature in K

Based on the above model, plume rise achieved was around 1238.4 m and assumed that stabilized cloud base is around 600 m altitude. The HYSPLIT simulation results depicted in Fig 6,7 and 8.

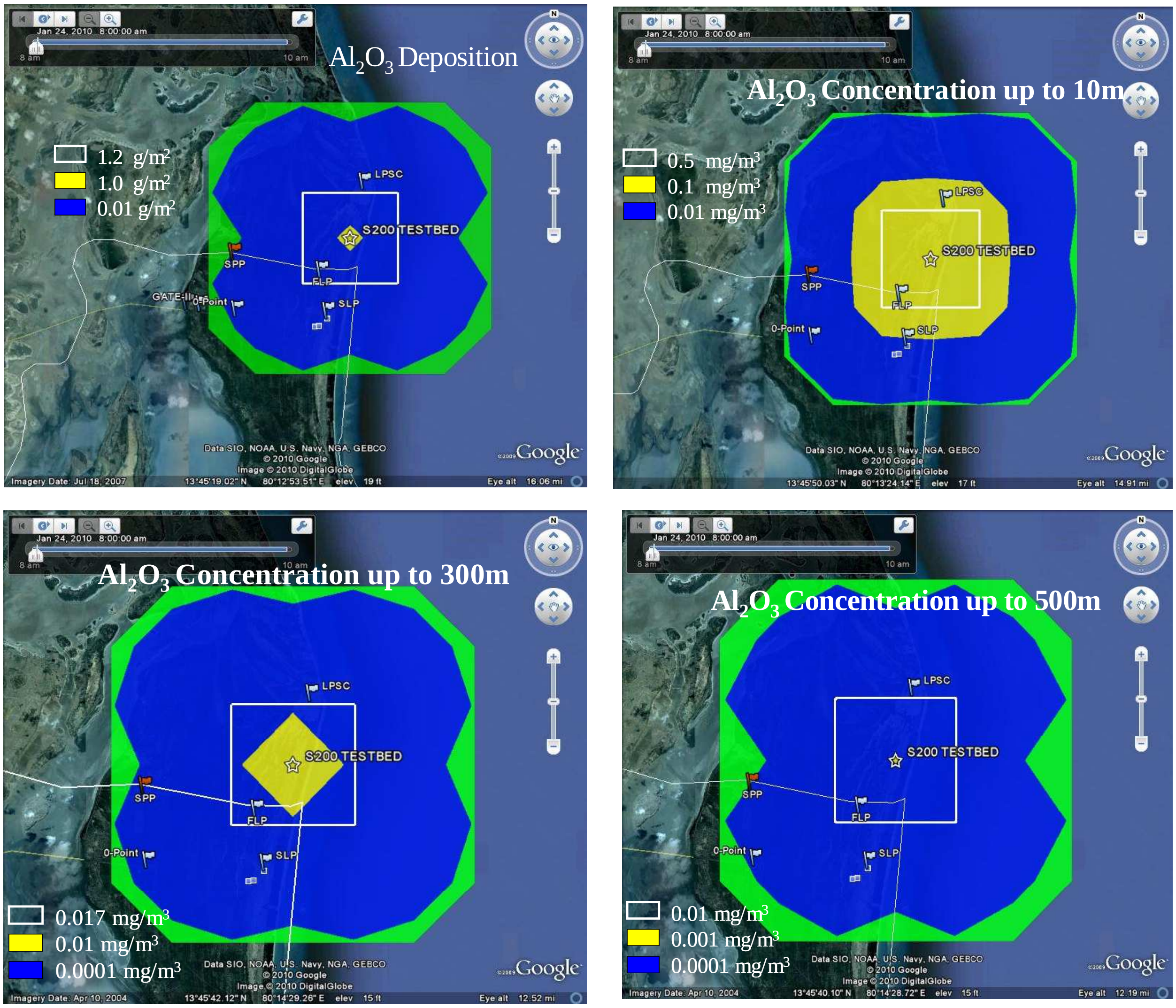


Fig.6 Deposition of Al_2O_3 at ground level, 10m, 300 m and 500m altitudes

HYSPLIT simulation of Al_2O_3 pollutant deposition in 5 km range of test bed is about 1.2 g/m^2. From test bed in 20 km range deposition is about 1.0 g/m^2. Al_2O_3 concentrations at 10m altitude is about 0.1 mg/m^3 up to 10 km range, at 300m altitude is about 0.017 mg/m^3 up to 10 km range and at 500m altitude is about 0.01 mg/m^3 up to 10 km range. The simulation results of deposition and dispersion of AL_2O_3 pollutant is uniformly distributed from surface to 500 m altitude.

HCl concentration at 10 m altitude simulation explains southward movement of plume with maximum concentration of about 1.4 ppm within 5 km range. At 500m altitude HCl concentration simulation shows the westward movement of the exhaust plume. The dispersion of the exhaust plume at upper level (500m altitude) is following the mean flow of the easterly wind, which was confirmed in local wind observation and MM5 simulations.

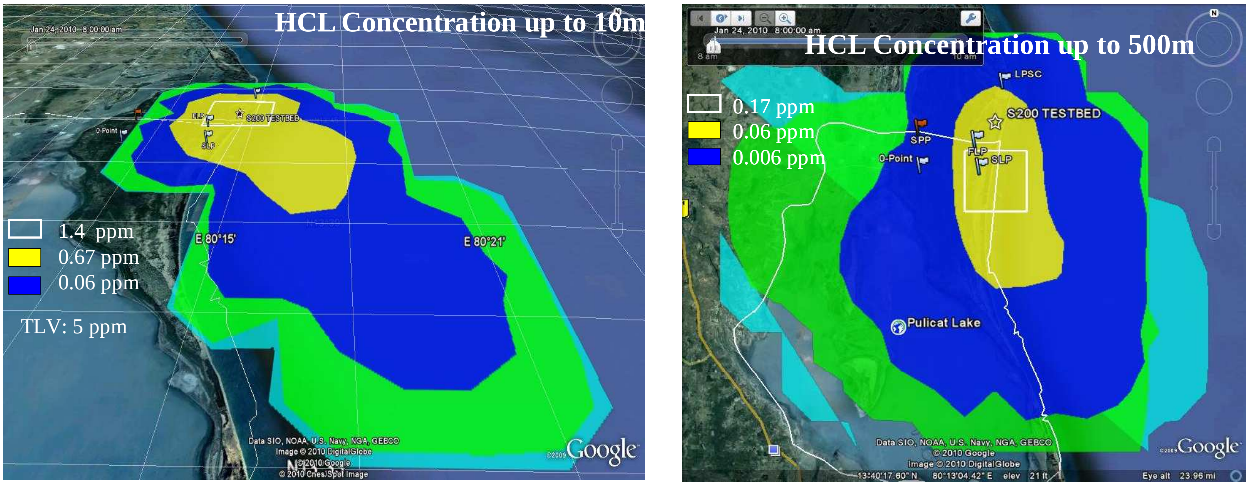


Fig.7 Dispersion concentration of HCl at 10m and 500m altitudes

10m and 500m altitude concentrations of CO within 5 km are 2.35ppm and 0.25ppm respectively. In this case also upper level concentrations is followed the mean wind flow direction is shown in Fig 7.

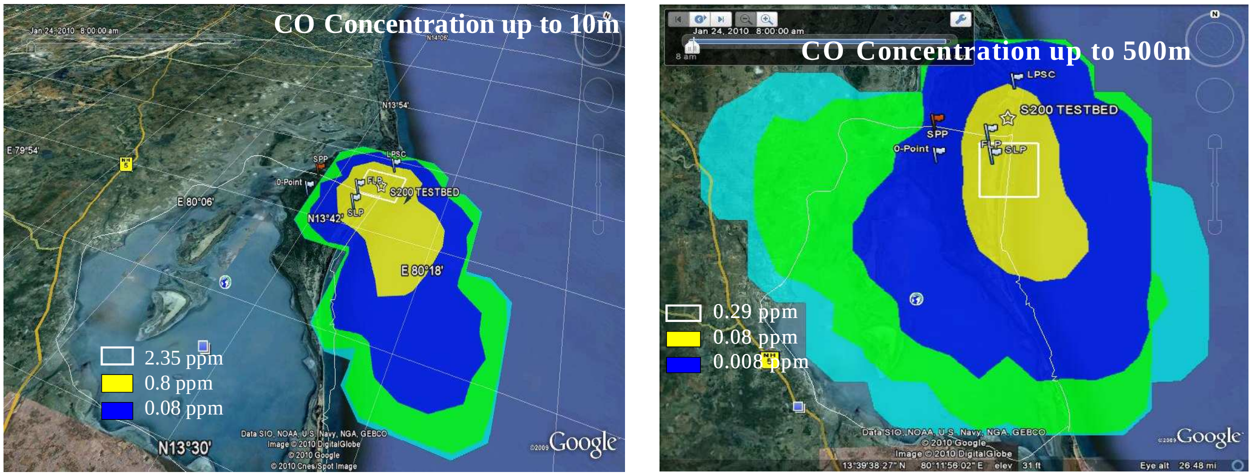


Fig. 8 Dispersion concentration of CO at 10m and 500m altitudes

8.0 Conclusion and Future Works

The configuration of the HYSPLIT model is very generic, it could be set up to perform a variety of different scenarios. In general Lagrangian models are well suited for quick calculations from pollutant point sources. The dispersion of Al_20_3, HCl and CO of S200 solid propellant rocket motor firing at different altitudes from surface to 500m is simulated and results are presented. The comprehensive validation of the HYSPLIT would be taken up with experimental observations for the further understanding of the short-range dispersion and model validation.

This may pave the way to stride towards the prediction of exhaust gas behavior of largest solid motor and future launch vehicles of Indian Space Research Organisation.

Acknowledgement

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